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The central hypothesis of this paper is that an optimal composit strategy coordinating the agents for achieving a minimum cost is obtained by an application of the Kohn-Nerode definition of continuity for hybrid systems. The effect is that we can now use infinitesimals to both define the choices available, and construct the equation to be solved. Secure in the knowledge that the optimization strategy for these highly nonlinear combinations is guaranteed to exist, we can guarantee that the finite approximations generated by MAHCA approaches the correct result. The body of the paper provides a notional description of the problem to be optimized (strategic mobility) and an overview of the multiple-agent architecture for extraction of an optimal exonomic policy law.

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Cost-Benefit Policy-Extraction Using a Multiple-Agent Hybrid Control Architecture (MAHCA)

Final Technical Report (CLIN 0002AE)
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Intermetrics, Inc.

Cost-Benefit Policy-Extraction Using a Multiple-Agent Hybrid Control Architecture (MAHCA)

Response to Downsizing: Reducing Costs by Distributed Optimization

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1. Executive Summary

The United States faces the problem of maintaining military preparedness in a declining fiscal resource environment. Economic analysis of alternatives for planning and budgeting of defense resources has occurred since Defense Secretary McNamara initiated the process in the mid-1960s. In the current circumstances, the application of traditional means of analysis for finding the optimum economic policy for the military is a major challenge. This paper presents newly available hybrid system methods which are applicable to economic policy modeling and provide effective procedures for optimizing difficult resource decisions.

The new hybrid control architecture (MAHCA) for the first time allows the implementation of a heterogeneous set of dynamic, simultaneous competitive optimization strategies. These strategies are interactively implemented by multiple agents participating in economic policy modeling and law extraction. The composite strategy derived from the application of the individual strategies, generates an optimal economic policy law for the implementation of resource allocation decisions such as acquisition, force structure, operations, or doctrine initiatives. This behavior is obtained in the presence of knowledge uncertainties, such as incomplete models of the systems being acquired, poorly defined operational threats, and evolving new doctrinal challenges.

The central hypothesis of this paper is that an optimal composite strategy coordinating the agents for achieving a minimum cost is obtained by an application of the *Kohn-Nerode definition of continuity for hybrid systems*. The effect is that we can now use infinitesimals to both define the choices available, and construct the equation to be solved. Secure in the knowledge that the optimization strategy for these highly nonlinear combinations is *guaranteed to exist*, we can guarantee that the finite approximations generated by MAHCA approaches the correct result in the limit [8]. The model of economic policy interactions is illustrated in Figure 1.

The body of the paper provides a notional description of the problem to be optimized (strategic mobility) and an overview of the multiple-agent architecture for extraction of an optimal economic policy law.

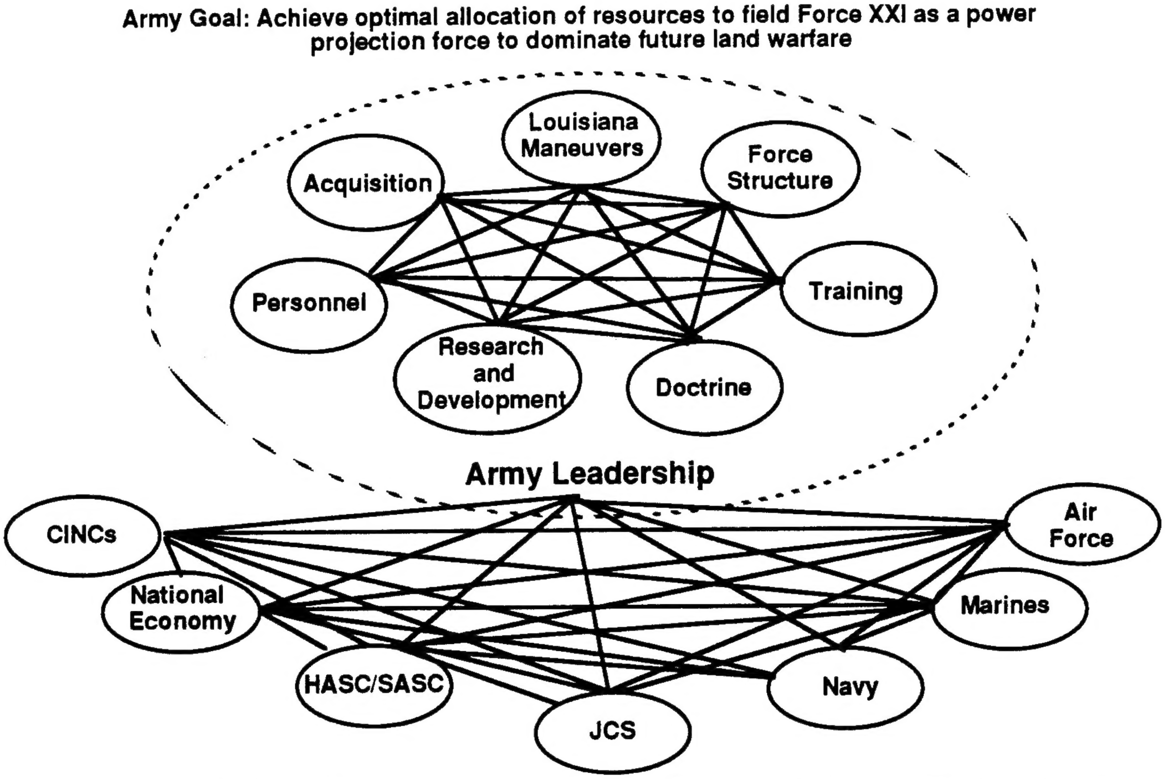

Figure 1. Model of Interacting Agents for Economic Policy Determination

2. Introduction

The new hybrid control architecture (MAHCA) for the first time allows the implementation of a heterogeneous set of dynamic, simultaneous competitive optimization strategies. By dynamic we mean that the parameters determining the outcomes of individual competitive optimization strategies change during the conduct of the competitive optimization (current approaches are static in the sense that these parameters are fixed during conduct of the competitive optimization). By heterogeneous competitive optimizations we mean optimization procesess which apply different criteria for determining a near optimal outcome (current analytical approaches apply a single competitive optimization strategy to analyze economic policy alternatives). We assume these heterogeneous competitive optimizations are implemented between multiple agents participating in economic policy modeling and law extraction (see Figure 1). The result of being able to model simultaneous heterogeneous competitive optimizations is that we can now capture the fact that different agents see the competitive economic cost process from different viewpoints (e.g. as an analogy consider multiple players of a board game where two players might decide to play the game of chess but two other

players might decide to play the game of checkers - with all players moving the same pieces!). Such a set of interacting policy strategies has been studied by economists for decades as a more accurate model of macroeconomic processes (cite Karl Shell). Moreover, economic models of heterogeneous competitive strategies are available for individual manufacturing, legislative, executive, enterprise, and other processes as well as rules for their effects on each other (cite Karl Shell). However, until the creation of MAHCA, the technology has not been available to solve a heterogeneous formulation of the economic policy problem. Using MAHCA, the composite strategy derived from the application of the individual strategies as a composite competitive optimization, extracts an optimum economic policy for implementation of **acquisition, operations, or doctrine initiatives**. This behavior is obtained in the presence of knowledge uncertainties, such as incomplete models of the systems being acquired, poorly-defined operational threats, and evolving changes in doctrine.

In Figure 1, the National economy is assumed to interact with other agents by applying a Pareto optimality criteria on all agents. While other considerations apply, the Army also interacts with the Commanders-in-Chief of unified and specified commands (CINCs), the legislative branch (House Armed Services Committee and Senate Armed Services Committee), the executive branch through the Joint Chiefs of Staff (JCS), and other services (Navy, Air Force, and Marines). Economic policy law formation is achieved by the network of interacting agents applying heterogeneous competitive optimization strategies (Figure 2).

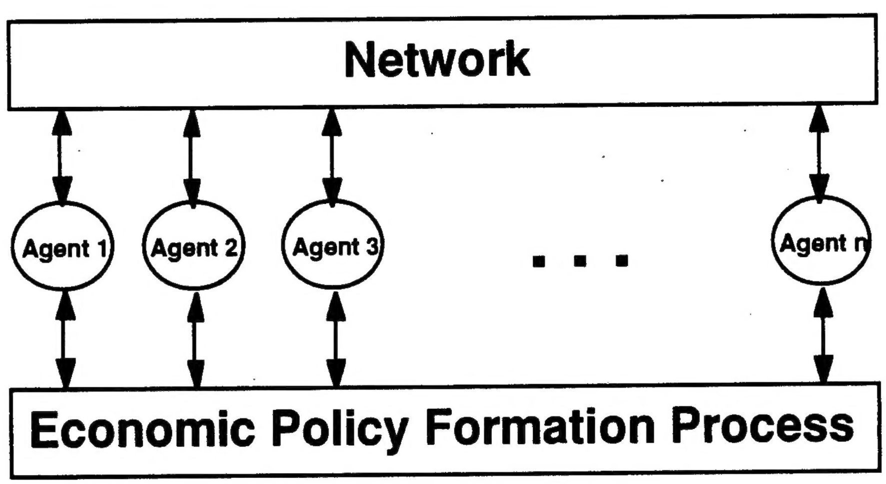

Figure 2. Cost Tool Configuration

Within the Army, the Army leadership might apply a Stackelberg[1] strategy to allocate resources among major components for doctrine analysis and revision, training in units and institutional training, incremental change of the force

[1] See Section 4.1 for definitions of competitive optimization strategies.

structure, acquisition and maintenance of materiel, recruiting personnel and maintaining morale, and research and development of new systems. Different major commands and functional Army agencies could apply a variety of competitive and teaming strategies with different agents. The Louisiana Maneuvers activity is seen as a major player in conducting an objective review of alternative strategies for determination of Army economic policy.

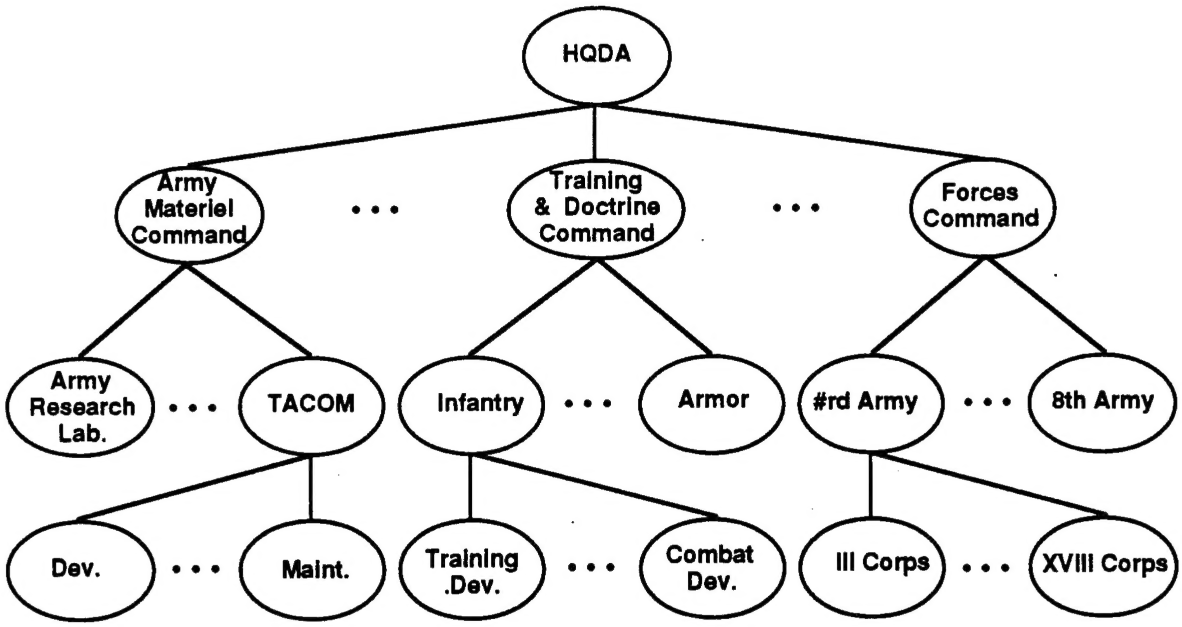

Figure 3. The Army TDA and MTOE as a Stakleberg Competitive optimization

The US Army Research Office (ARO), the US Army Armaments Research, Development and Engineering Center (ARDEC) and the Advanced Research Projects Agency (ARPA) are currently supporting the development of the new technology discussed in this paper. The technology being developed is one which exhibits both continuous and discrete behavior. In this paper we outline how this technology can be applied to economic utility theory using a Multiple-Agent Hybrid Control Architecture (MAHCA). In that context, we may wish to consider issues associated with resource allocation for optimized tradeoffs between strategic mobility and combat effectiveness for Force XXI. The Army uses the framework of the Concepts-Based Requirements System to achieve conflicting goals present in long-range planning. Our intent is to use a revised CBRS process to support the Louisiana Maneuvers initiative to demonstrate how our new technology could help evaluate alternative futures for the Army.

For example, we may wish to consider characterizing the cost-benefit analysis of improving the material-handling capability of the military transportation system by increasing the throughput of the existing infrastructure. Different cost-benefit

policies for such an analysis might be (1) examine the cost benifits of prepositioning warfighting equipment in unit sets at different locations for the purpose of improving infrastructure throughput or, (2) examine the cost benifits of applying new manufacturing technology for decreasing the costs of transporting material by increasing combat power of the delivered task force, or (3) examine costs based on maintaining technical quality of prepositioned warfighting equipment by a product improvement of the stored combat systems, always based on improving infrastructure throughput (see Figure 3). We contend that basing such a cost-benefit analysis on Advanced Distributed Simulation requires a scalable architecture which will support aggregation from the smallest component under consideration for analysis to the highest levels of military command structure and which can be synchronized with other pertinent systems. A first start in achieving such an analysis capability is a rigorous statement of the problem in the MAHCA framework.

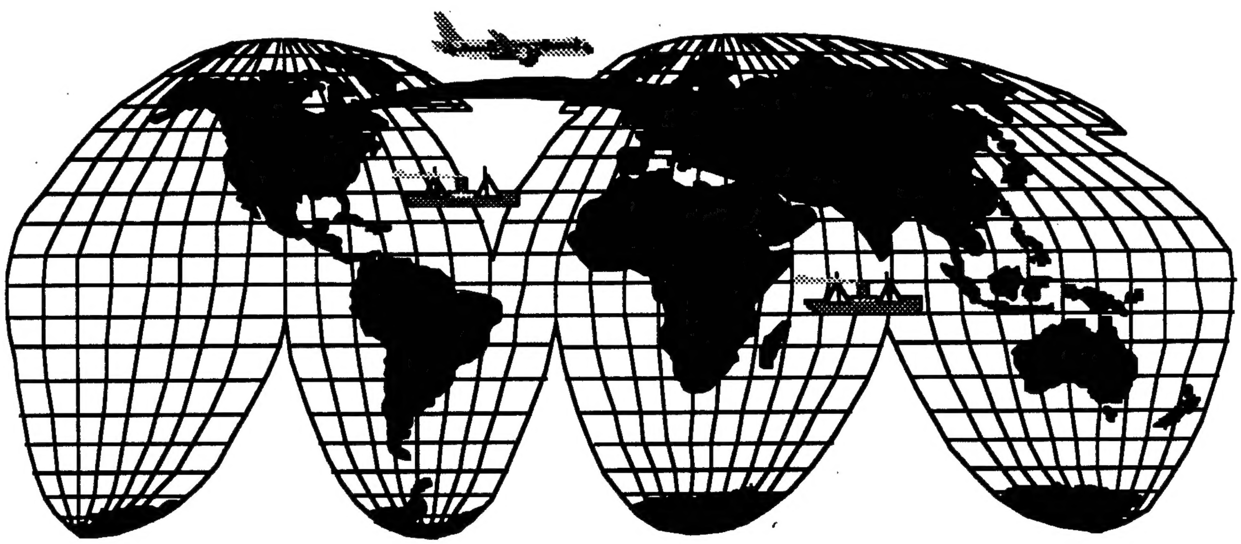

Figure 3. A Strategic Mobility Problem

In order for the consideration to be consistent with the Army's way of doing business, we will include the constraints of the CBRS. The CBRS principle: investment choices are based on *concepts for executing warfighting doctrine.*

Typical considerations which may affect prioritization decisions include: Operational concept (employment of Division/Corps maneuver forces), System concept (employment of crew-served weapon system), Battlefield Functional Mission Area (BFMA) concept (employment of fire support), Branch Concept (employment of light infantry), and Priority to First-to-Fight for each type of force (Active Component and Reserve Component).

3. The Cost-Benefit Policy Problem and Prioritization of Army Investments

The hypothesis of the proposed cost-benefit policy problem is the following:

If the agents in the process interact according to competitive optimization strategies that satisfy requirements, then the resulting policy will produce lower costs than if team strategies would have been used.

The intuitive explanation behind this hypothesis is that in any of the considered cost processes (acquisition, operations, doctrine) the actions (i.e. the moves) of each agent are constrained not only by its own requirements but also by the other participating agents forcing compromises (according to the competitive optimization strategies) that would not be included in a team formulation.

For example, in an operation for prepositioning warfighting equipment, conflicting goals are present in trying to (1) maximize the combat effectiveness of the equipment, while at the same time attempting to (2) maximize the size of the force supported by the equipment, (3) maximize the compatibility of the stored equipment with the equipment used by the deploying units, and (4) maximize the length of time the stored equipment will be operationally effective. These goals lead to a need for the *comparison* of costs for *maintaining technical quality* of prepositioned warfighting equipment configured in unit sets (which might be achieved by a product improvement) to *improving transportation throughput* (which might rely on use of a new manufacturing technology). Suppose the prepositioned equipment did not have the new throughput attributes (or the most effective version). A new manufacturing process might be under development which would impact acquisition costs, installation costs, operation and maintenance costs and performance capabilities of the prepositioned equipment or its replacements. The concept for Louisiana Maneuvers envisions that technical advances will be made which will increase combat effectiveness of individual weapons systems (and throughput of transportation assets) at the same time that new warfighting doctrine will be developed which will increase combat effectiveness of deployed forces. Both technical and doctrinal advances would be affected by increased logistical throughput to the battlefield.

4. MAHCA

In section 4.1 we will formulate the problem of implementing a cost-benefit policy analysis in a multiple-agent hybrid control architecture (MAHCA). First we provide an overview of MAHCA. Our approach is based on the establishment of a distributed team of reasoning agents connected in a possibly time-varying, competitive optimization network (see Section 4.5 for a notional overview and the separate technical paper for a detailed description of the architecture).

MAHCA consists of a variable network of interacting agents. The behavior of each agent is characterized by a *model* encoded in a hierarchy of coupled logic clauses. This model includes the competitive optimization rules associated with the competitive optimization strategy for each agent as it competes with the other agents in the network. The hierarchy also includes rules defining conditions of logic failure (i.e. when the model and the behavior observed by the agent are not in agreement) and rules for the activation of structural adaptation processes for recovery from failure. Logic failures may occur due to predictable and/or unpredictable events affecting the behavior of the processes under control of the agent or due to the fact that the solution set of the competitive optimization which the agent is implementing is empty for the current situation. Adaptation is accomplished by the modification of the logic clauses, according to composite rules from a fixed set of primitive modification rules, or by the creation or deletion of agents in the network.

The appropriate reaction to a failure is logically *deduced* from a dynamic knowledge base which contains relations encoding the operational parameters characterizing the system under cost evaluation. Each agent acts to generate actions at a node in the network, the agent's competitive optimization "moves". These "moves" can also adapt in accordance with pre-specified or deduced constraints.

The set of primitive modification rules are: Derivation, Combination, Abstraction, Relaxation and Deactivation.

A derivation rule generates a clause that is a logical consequent of a given subset of encoded clauses. A combination rule uses logical connectors 'and' , 'or' or 'not' appending a subset of encoded clauses to form a new valid clause. An abstraction rule changes the domain of resolution of a given rule to that of a congruent version of this domain. A relaxation rule changes the time step in a rule according to the approximation to optimality. A deactivation rule deselects or disables a subset of clauses from the current set of active clauses.

Our architecture provides a knowledge-based, formal framework for deducing on-line feedback competitive optimization moves and reactive strategies for dynamic processes involving multiple agents. The architecture also includes capabilities for implementing the competitive optimization adaptation-by failure-function described above. These adaptation characteristics explicitly address the need for restating the competitive optimizations being implemented when the agreement set is empty.

4.1 Competitive optimization strategies in MAHCA

The agents illustrated in Figure 1 may use several different strategies. In fact they may execute a different strategy on each other agent with which they interact. We give a brief description of some of the possible strategies here. The description of how strategy execution is guided is often referred to as *mood* in competitive optimization theory literature.

TEAM STRATEGY. The mood of *team strategy* is utopian cooperation in which the individual agents seek to minimize cost for themselves without raising cost for the other agents. *Team strategy* is sometimes referred to a utopian cooperation. For *team strategy*, the agreement set becomes a single point in cost space.

PARETO STRATEGY. The mood of Pareto strategy is non-utopian cooperation, in which each agent is willing to forgo a cost benefit if it is at the expense of other agents. Decisions which decrease the cost to at least one agent without increasing cost to any other agent are acceptable under Pareto. The agreement set is the set formed by the locus of points of tangency of cost contours.

NASH STRATEGY. The mood of Nash strategy is non-cooperative with each agent striving to minimize his own cost while giving no regard to the consequences for the other agents. When a state of equilibrium is obtained under Nash strategy, no one agent can gain further advantage by changing decisions. The agreement set is the intersection of least cost trajectories (of the individual agents) in cost space.

MIN-MAX STRATEGY. This is a two-agent strategy in which the total cost shared by the agents is fixed. The mood of play is non-cooperative. Thus, each agent assumes that each agent will strive to minimize his own cost at the expense of the other agent. The strategy thus becomes one of minimizing the consequence of the opponents worst possible decision. Finally, each agent is seeking to minimize the extent to which the opposing agent can maximize the agent's own cost.

STACKELBERG STRATEGY. The mood of the Stackelberg strategy is cooperative. One agent acts as the "commander" and constrains the decision options of other agents, the "executors". The commander agent minimizes the cost for each of the decision variables and the decision variables of each of the executor agents become functions of the commander's decisions. Each executor agent has an agreement set with the commander. In this mood, each executor agent interacts with the commander, not with one another.

4.2 State of Knowledge of our Multiple-Agent, Hybrid Control Architecture (MAHCA): We provide the following summary of results for MAHCA:

1. Our formulation gives a precise statement of the heterogeneous competitive optimization problem in terms of multiple agent hybrid declarative control. Our approach characterizes the problem via a knowledge base of equational

rules that describes the dynamics, constraints and requirements of the processes characterizing the domain in which the competitive optimizations are being executed. The goal of each agent in the competitive optimization is to minimize its overall cost according to the competitive optimization strategies it is involved in.

2. Our approach is based on a canonical procedure to prove that a goal clause (a special class of existentially quantified clauses). A goal clause characterizes the desired behavior of the domain process, that is, a state trajectory of the process in which the agent is involved satisfies certain requirements.. The procedure determines a resolution, with respect to the current knowledge base status, by constructing and executing on-line a finite state machine called the "proof automaton." The output function of this automaton generates the control actions the agent uses to control the aspects of the process in which it is involved.

This is the basis for extracting competitive optimization policy laws for generating cost models. MAHCA will support incremental expansion of new agents and knowledge with greatly reduced requirements for expensive experimentation and validation. We do not expect to fully eliminate the need for experimentation because the degree of "trust" in the newly composed architecture will depend on the clauses characterizing the process. However, to the degree that the competitive optimization and requirement clauses are correct, MAHCA generates formally correct cost estimates. The focus of the verification and validation effort will be raised to the agent level and the results will be reusable across the confederation of agents.

4.3 How the existing hybrid systems unification mechanism works:

Here is the underlying architecture in a nutshell. Each agent is assigned a non-negative local cost function rate which is a function of the local state, and agent action. The local state is that part of the global state of the system which is observed or estimated from appropriate economic indicators by that agent or provided by other agents. The agent chooses local state dependent actions to exercise on the environment which will minimize the integral of the cost function rate along its local state trajectory. An economic policy for that agent is one which takes its local current internal state and the local state of the environment as inputs and produces the required action on the environment as output.

The cost function rate for an agent is chosen to assure that a policy for its cost function achieves a value near optimal behavior with respect to the corresponding agents participating in each of the min-max, Pareto, Stackelberg, or Nash strategies in which the agent is participating. For example if an agent is participating in a

Nash strategy with two other agents and in a Pareto strategy with three others, its policy for the heterogeneous strategy will be an appropriate mixture so that the agent achieves near optimality in both competitive strategies.

A characteristic feature of the Kohn-Nerode multiple-agent architecture is that the sole form of direct interaction between the agents is that at appropriate intervals (dictated by events) an agent passes a message consisting of a cost function rate term to other agents. Each term sent from agent i to agent j is interpreted as a penalty, i.e. the increase in agents j's cost, agent i imposes on agent j for deviation from desired behavior, increasing agent j's costs.

The agent chooses control actions on the environment which approximately minimize the resulting cost function and runs open-loop based on this control action till the next such exchange of information.

The mathematical device we use convexifies the problem and extracts optimal policies for the convexification which are measure-valued. Until Kohn's work, this was regarded as physically meaningless. However, finite approximations that can be computed in real time for such a measure-valued control yields so-called *chattering* controls that provide near optimum policies for each of the agents in accordance with its own cost functional.

To our knowledge, the Kohn-Nerode approach to hybrid systems is the only theory to both (1) provide a solid mathematical foundation to unify both logical and evolution models and (2) be computationally feasible. The methodology, while promising, is very new and research is required to understand both the most effective ways to construct the unified models and to build the necessary interfaces to existing systems. However, recent demonstrations for the Army and the Advanced Research Projects Agency substantiate that software is available to implement the first phase of a tool for economic analysis based on MAHCA. In addition, the rapid acceptance of the theory by major research institutions attests to its relevance to fundamental issues in several disciplines.

4.4. Hybrid systems and integration of heterogeneous models:

Consider the problem of creating economic comparisons of alternative policies for achieving strategic mobility for Force XXI. The policy which would result in maximizing the throughput capability for delivering unit material into the area of operations using airlift will conflict with the policy which would maximize the throughput capability for delivery using sealift.

The policy which attempts to maximize total weight delivered into the area of operations will conflict with the policy which attempts to minimize the time to

deliver the first operational combat brigade into the area of operations. Moreover, the length of time needed to implement incremental change in force structure combat power means that the equipment stored in prepositioned unit sets will not match the equipment used by the units in their home stations. Technical advances for increasing combat effectiveness will necessarily be "traded off" for changes in doctrinal execution of operational decisions.

These considerations indicate that an accurate model of cooperative and non-cooperative strategies for economic comparison requires a composite set of strategies instead of relying on a single strategy.

4.5 Functional characteristics of architecture

The Multiple Agent Hybrid Architecture is implemented on the computer through a declarative controller logic paradigm. This paradigm implements a planner an inferencer, an adapter and a knowledge decoder. Figure 5 shows the top clause of the implementation for this paradigm.

The planner accepts input data concerning local economic indicators and goals for the allocation of resources; it generates desired behavior for the current update interval as a convex optimization statement for the desired behavior.

If there exists a solution of the optimization problem generated by the planner that is compatible with the current status of the knowledge base, then the inferencer generates the agent actions. If the desired behavior is true in this sense, then a side effect is the instantiation of command actions and an update of the state data.

If the solution of the optimization problem is not compatible with the current instantiation of the knowledge base, then the offending terms are sent to the adapter for correction. Corrected terms are fed to the planner and incorporated in a modified description of the desired behavior.

The knowledge base stores in an equational clause format requirements, competitive optimizations rules, process dynamics, and the values of economic indicators. It also stores rules for interagent coordination and the rules for solving the optimization problem.

The knowledge decoder translates interagent network data into agent's knowledge base.

The functional relationships among these components is shown in figure 6.

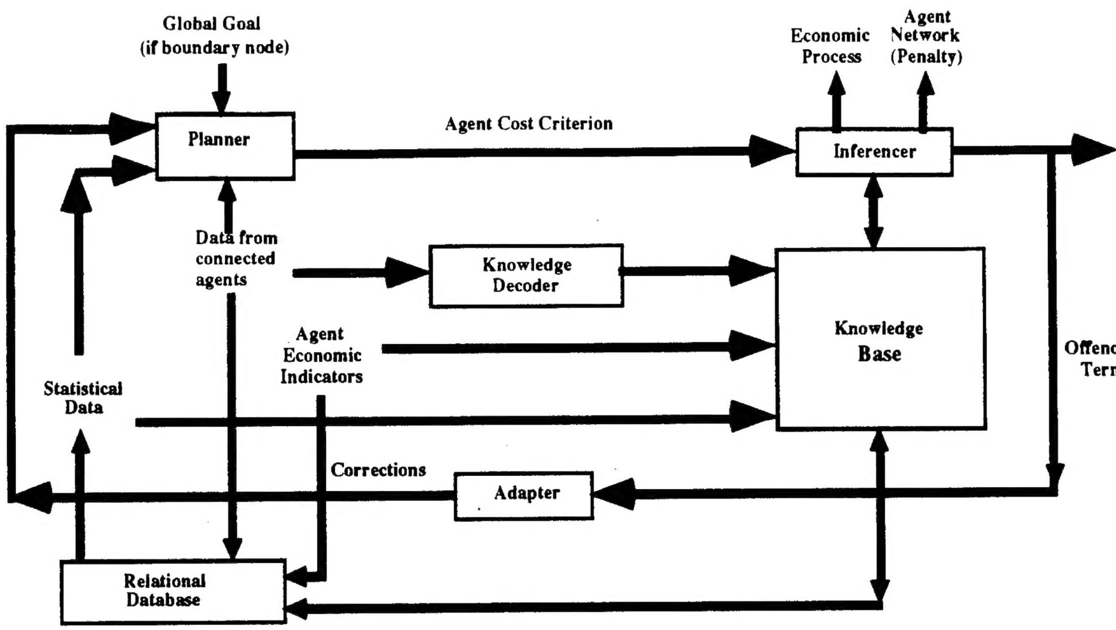

Figure 6. Declarative Agent Architecture

5. Project overview

6. Conclusions.

This formulation provides a unique tool for evaluating and generating cost policies. The hetrogeneous competive strategies proposed model more accurately the true interaction between organizations particpating in various economic processes. The tools that we have developed in the multiple agent hybrid control architecture (MACHA) can be adapted to handle situations where an agent or organization must employ several optimization strategies depending on which other agent or organiation wiith which it interacts. This collection of agents for modeling economic choices is precisely the capability that the Army Staff requires to assist Army leadership in conducting analysis of tradeoff alternatives for building Force XXI.

Items from notes plus

Bibliography